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Topical White Paper:

Fundamental Physics with Strongly Interacting Ultracold Matter in Microgravity

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1 Introduction

This white paper advocates a research program that focuses on the study and manipulation of strongly interacting ultracold quantum matter. Microgravity offers unique opportunities for the study of fundamental physics in such systems at an unprecedented level of accuracy and control.

Quantum mechanics is the science of the very small, and is thus of extreme fundamental and technological relevance. With tunable interaction strength, variable density, and a wide variety of probing techniques, ultracold quantum gases provide an excellent system for exploring quantum phenomena. In the past few years, the progress made in ultracold quantum gases has increasingly been translated into promising prospects for coherent quantum control with applications for fundamental science and quantum technologies [1–4]. Despite the rapid progress, the presence of gravity, and thus the need to confine the quantum gases in atom traps, is clearly posing limitations. As is laid out below, a microgravity environment offers new avenues to overcome existing limitations and enter into new regimes. For example, new possibilities to achieve coherent control over few-body interactions will provide ways in which one can produce exotic quantum phases that are solely controlled by few-body interactions. In fact, among all the unique properties of ultracold quantum gases, the ability to control interatomic interactions [3] is one that set this system apart from others in a very fundamental level. Studies of few-body interactions promise a particularly high pay-off: few-body interactions are responsible for a number of collective phenomena relevant across a broad range of physical systems. In particular in the regime of strong interactions, the ability to control interacting ultracold quantum matter will enable the exploration of a complex array of quantum phenomena that interconnect a number of different physics subfields, especially atomic, molecular, optical, condensed matter, nuclear physics, and chemistry. It is anticipated that studies in this direction can have the potential to impact every experiment in the strongly interacting regime (on microgravity or on ground).

The first glimpse on the importance of understanding few-atoms processes in ultracold quantum gases dates from the early years after the creation of the first dilute gas Bose-Einstein condensate [5–8]. Few-atom losses limit the lifetime and stability of condensates and still represent a major obstacle for the experimental exploration of many fundamental physical phenomena in a strongly-correlated ultracold gas. Moreover, much of what is understood today about the collective behavior of quantum matter relies on the properties of two-body physics, leaving aside high-order correlations originating from few-body physics (three or more interacting particles). In particular, whenever the atomic interactions are strong, an infinity of triatomic Efimov states are formed even though two particles do not interact strongly enough to bind a single diatomic molecular state [5–10]. Predicted nearly 50 years ago, the Efimov effect is a counterintuitive effect that brings forth the promise of a new level of control and understanding of various fundamental aspects of strongly interacting quantum matter and for exploring novel exotic dynamical regimes. Although earth-based experiments have reached maturity in terms of their technical capability, there is still much to be explored to determine how to utilize few-body interactions in order to engineer novel exotic quantum regimes. Most of these physical regimes and phenomena would benefit from microgravity environments as it alleviates the need to support against gravity and avoids unwanted perturbing factors, thus allowing for a much cleaner and more stable platform to explore quantum dynamics and interactions.

Few-body interactions bridge the gap between the two-body physics explored in much of AMO physics and the many-body physics underlying condensed-matter physics. Controlling and exploiting few-body interactions represents one of the next frontiers in the research of ultracold quantum matter and should be considered as a main focus of NASA's space-based fundamental physics research program from 2023-2032 for the advancement of quantum science and technologies.

2 Current Status and Microgravity Justification

An increasingly large number of ground-based experiments with ultracold atoms have been designed for the exploration of few-body physics, having provided many observations of the Efimov effect [5–7, 11, 12] and of other few-body related phenomena [13–22]. Observations in the strongly interacting regime, however, are limited by the fast time scales associated with losses which limit the scope of what can be reliably measured on earth. This precludes clear observations of excited Efimov states and, more fundamentally, the verification of various universal properties of the system. Moreover, because losses add incoherence to the system, the observation of collective phenomena in the strongly interacting regime is difficult.

Microgravity environments, like those found at the NASA's Cold Atom Laboratory (CAL) facility on the International Space Station (ISS), allow for orders of magnitude lower densities and temperatures than experiments on earth and represent a paradigm shift for future explorations of strongly interacting quantum matter. Under such conditions, losses are suppressed and the exploration of large Efimov states - unlikely to ever to be observed on earth - becomes possible. The extended atom-atom coherence afforded by the absence of gravity is also a key aspect that can facilitate the manipulation of few-atom correlations necessary to explore novel quantum phases of the matter.

3 Opportunities

Below, we will list and briefly discuss a number the opportunities that we believe will have a substantial impact on the research of strongly interacting quantum matter. In some of the opportunities the presence of a microgravity environment is imperative, while in others the use microgravity can also inform paths to earth-based studies and vice-versa.

Efimov States and Resonances. The study of excited Efimov states and resonances is an opportunity that directly benefits from the microgravity environment. Excited Efimov states are extremely large, so large that they can exceed the average interatomic distances for typical ground-based experiments, making them difficult to access [23–25]. They are also extremely weakly bound, and thus susceptible to thermal fluctuations and trapping disturbances. The ultralow density and temperature regimes achievable in microgravity, along with the nonnecessity of trapping atoms against gravity, make this environment a much more stable platform for the study of such delicate systems. This will allow one to approach a regime where Efimov universality is at its best, i.e., the regime where interactions are extremely strong, and the states far exceed all other length scales that introduce non-universal effects [11, 12].

So far, various universal predictions relating different manifestations of Efimov physics [8, 26, 5] remain unobserved. In particular, the connection between excited Efimov resonances and interference effects have not beeen verified due to the limited access to stronger interactions and thermal effects [5]. Besides allowing for access to the regime where these universal aspects can be verified, microgravity will also allow for the exploration of novel resonances and scattering regimes. For example, the existence of four-body resonances in dimer-dimer collisions [27] could lead to the realization of molecular gases with tunable interactions as well as to provide a highly efficient way for create Efimov trimers.

Quenched Unitary Quantum Gases. Understanding strongly correlated phases of matter following a Hamiltonian quench is a fundamental challenge in modern science as it requires a new understanding of the thermodynamic properties of out-of-equilibrium isolated quantum systems. That includes studies of the early universe after inflation [28–31] and of quark-gluon matter generated in heavy-ion collisions [32–34]. Despite the success of statistical mechanics in describing classical systems, reconciling the irreversible character of thermodynamics with the time reversibility of isolated quantum systems has only recently found a more solid foundation based on the eigenstate thermalization hypothesis (ETH), deeply rooted in quantum chaos, and has been the focus of intense theoretical investigations ever since [35–46]. Over the past few years, the study of quenched unitary Bose gases has also greatly intensified due to the experimental [47–58] and theoretical [59–85] advances with ultracold atoms. Although ultracold quantum gases have extremely low densities, the unique ability to control the strength of the interatomic interactions allows one to probe the *unitary regime*, where the probability for collisions can reach unity and the system becomes highly non-perturbative. In contrast to their fermionic counterparts [86–88], adiabatically approaching the unitary regime in a Bose gas is practically impossible due to fast atomic losses [89, 90]. Recent experiments [47–58], however, reached the unitary regime by quenching the interatomic interactions from weak to infinitely strong using Feshbach resonances [3]. This scheme has allowed the system to live "long enough" to observe the dynamical evolution and equilibration of the unitary Bose gas thanks to the slow three-body decay rates produced in quenched system [65].

In a micrograticvy environment, due to the ability to reach ultralow densities and temperatures, the expected lifetimes are much more favorable, thus allowing for longer interaction times and a more in-depth probe of the dynamical properties of quenched unitary Bose gases. As shown in Refs. [79, 80], this is particularly important considering the fact that higher-order correlations such as those generated by Efimov physics typically evolve only at longer times than observed in ground based experiments. Therefore, by making the unitary regime more accessible, studies in microgravity will also allow for the exploration of the connection between three-body Efimov physics and collective dynamics of unitary Bose gases [81, 83], novel pair formation [82] and alternative paths to reach unitarity [84, 85]. Moreover, unitary Bose gases in microgravity will provide an unique platform to study quantum few- and many-body non-equilibrium dynamics in a controlled manner.

Few-body Driven Phases of the Matters. Few-body interactions are responsible for a number of collective phenomena relevant across a broad range of physical systems. For ultracold gases a number of regimes were predicted centered around the role of the three-body interactions [91–95] but of particular interest are those phenomena where interactions are tunable and/or the Efimov physics play a major role [96–106]. Here, we will highlight two of these oppotunities which are expected to have a major impact on the fundamental understanding of ultracold quantum matter and beyond.

Efimov Liquids. In the context of a unitary Bose gas, the work in Refs. [102, 103] has predicted that, for sufficiently low temperatures and pressure, the system undergoes a first-order phase transition from a normal gas to a "superfluid Efimov liquid", where the atomic bounds have the same nature than those of Efimov trimers. A triple point separates these two phases and the BEC phase, whose coexistence line with the Efimov liquid ends in a critical point. Under experimental conditions found on earth, the observation of such a state is limited because it requires that the energy of the Efimov ground state to be much larger than those of the trap excitations, thus implying a highly unstable regime. At ultralow densities, however, it is possible to consider the same effect but now caused by an excited Efimov state, which has a lifetime about a factor 500 longer.

Quantum Droplets. It is well know that a Bose gas with attractive interactions is unstable and eventually collapses [107]. The work in Ref. [104], however, showed that a three-body repulsive interaction can stabilize the system into a quantum, self-bound, droplet phase. This regime can be achieved by tuning the interactions near an Efimov resonance where the three-body interaction can be independently tuned from attractive to repulsive. Although one can stabilize the system against collapse, the time scales for atom losses can still be too fast, preventing the system to transition to the droplet phase. Here again, the ultralow density regime can allow for more stability and observation of the droplet phase. As discussed below, ideas for further stabilization using coherent control can also be implemented in order to easy the access such collective phenomena.

4 Conclusions

Undeniably, experiments with strong interactions are challenging. The major challenge for such experiments has been to circumvent few-body losses, which limits the lifetime and stability of condensates on time scales much shorter than any collective phenomenon. This prevents detailed studies and observations of novel strongly interacting phases of matter. It is true that reducing the atomic density will reduce the time-scales of few-body losses. However, reducing the atomic densities will simultaneously scale-down the time scales for phase transitions as well. This reduction will probably not occur at the same rate but will potentially still cause dephasing and drive the system away from the strongly interacting regime. Therefore, when exploring phase transitions in the strongly interacting regime, a much more impactful way to pursue such explorations is by coherently controlling few-body processes. In this context, at the ultralow densities and temperatures achievable in microgravity, the coherent manipulation of large, weakly bound few-body states, such as Efimov states, is a favorable path to control of atomic losses. The achievement of coherent control over few-body interactions will also provide ways in which one can produce exotic quantum phases that are solely controlled by few-body interactions. Therefore, we believe that studies in this direction and the directions detailed above have the potential to impact every experiment in the strongly interacting regime (on microgravity or on ground).

References

[1] Franco Dalfovo, Stefano Giorgini, Lev P. Pitaevskii, and Sandro Stringari. Theory of bose-einstein condensation in trapped gases. *Rev. Mod. Phys.*, 71:463–512, Apr 1999. doi:10.1103/RevModPhys.71.463.

[2] Immanuel Bloch, Jean Dalibard, and Wilhelm Zwerger. Many-body physics with ultracold gases. *Rev. Mod. Phys.*, 80:885–964, Jul 2008. doi:10.1103/RevModPhys.80.885.

[3] Cheng Chin, Rudolf Grimm, Paul Julienne, and Eite Tiesinga. Feshbach resonances in ultracold gases. *Rev. Mod. Phys.*, 82:1225–1286, Apr 2010. doi:10.1103/RevModPhys.82.1225.

[4] Luca Pezzè, Augusto Smerzi, Markus K. Oberthaler, Roman Schmied, and Philipp Treutlein. Quantum metrology with nonclassical states of atomic ensembles. *Rev. Mod. Phys.*, 90:035005, Sep 2018. doi:10.1103/RevModPhys.90.035005.

[5] J. P. D'Incao. Few-body physics in resonantly interacting ultracold quantum gases. *J. Phys. B*, 51:043001, 2018. doi:10.1088/1361-6455/aaa116.

[6] Y. Wang, J. P. D'Incao, and B. D. Esry. Ultracold few-body systems. *Adv. At. Mol. Opt. Phys.*, 62:1, 2013. doi:https://doi.org/10.1016/B978-0-12-408090-4.00001-3.

[7] P. Naidon and S. Endo. Efimov physics: a review. *Rep. Prog. Phys.*, 80:056001, 2017. doi:10.1088/1361-6633/aa50e8.

[8] Eric Braaten and H. W. Hammer. Universality in few-body systems with large scattering length. *Phys. Rep.*, 428:259–390, 2006. doi:https://doi.org/10.1016/j.physrep.2006.03.001.

[9] V. Efimov. Low-energy properties of three resonantly interacting particles. *Sov. J. Nuc. Phys.*, 29:546, 1979.

[10] V. Efimov. Energy levels of three resonantly interacting particles. *Nucl. Phys. A*, 210: 157, 1973. doi:https://doi.org/10.1016/0375-9474(73)90510-1.

[11] Roman Chapurin, Xin Xie, Michael J. Van de Graaff, Jared S. Popowski, José P. D'Incao, Paul S. Julienne, Jun Ye, and Eric A. Cornell. Precision test of the limits to universality in few-body physics. *Phys. Rev. Lett.*, 123:233402, Dec 2019. doi:10.1103/PhysRevLett.123.233402.

[12] Xin Xie, Michael J. Van de Graaff, Roman Chapurin, Matthew D. Frye, Jeremy M. Hutson, José P. D'Incao, Paul S. Julienne, Jun Ye, and Eric A. Cornell. Observation of efimov universality across a nonuniversal feshbach resonance in ^{39}K. *Phys. Rev. Lett.*, 125:243401, Dec 2020. doi:10.1103/PhysRevLett.125.243401.

[13] A. M. Kaufman, B. J. Lester, C. M. Reynolds, M. L. Wall, M. Foss-Feig, K. R. A. Hazzard, A. M. Rey, and C. A. Regal. Two-particle quantum interference in tunnel-coupled optical tweezers. *Science*, 345(6194):306–309, 2014. doi:10.1126/science.1250057.

[14] A. M. Kaufman, B. J. Lester, M. Foss-Feig, M. L. Wall, A. M. Rey, and C. A. Regal. Entangling two transportable neutral atoms via local spin exchange. *Nature*, 527:208, 2015. doi:10.1038/nature16073.

[15] F. Serwane, G. Zürn, T. Lompe, T. B. Ottenstein, A. N. Wenz, and S. Jochim. Deterministic preparation of a tunable few-fermion system. *Science*, 332(6027):336–338, 2011. doi:10.1126/science.1201351.

[16] G. Zürn, A. N. Wenz, S. Murmann, A. Bergschneider, T. Lompe, and S. Jochim. Pairing in few-fermion systems with attractive interactions. *Phys. Rev. Lett.*, 111: 175302, 2013. doi:10.1103/PhysRevLett.111.175302.

[17] A. N. Wenz, G. Zürn, S. Murmann, I. Brouzos, T. Lompe, and S. Jochim. From few to many: Observing the formation of a fermi sea one atom at a time. *Science*, 342 (6157):457–460, 2013. doi:10.1126/science.1240516.

[18] Simon Murmann, Andrea Bergschneider, Vincent M. Klinkhamer, Gerhard Zürn, Thomas Lompe, and Selim Jochim. Two fermions in a double well: Exploring a fundamental building block of the hubbard model. *Phys. Rev. Lett.*, 114:080402, 2015. doi:10.1103/PhysRevLett.114.080402.

[19] S. Murmann, F. Deuretzbacher, G. Zürn, J. Bjerlin, S. M. Reimann, L. Santos, T. Lompe, and S. Jochim. Antiferromagnetic heisenberg spin chain of a few cold atoms in a one-dimensional trap. *Phys. Rev. Lett.*, 115:215301, 2015. doi:10.1103/PhysRevLett.115.215301.

[20] L. R. Liu, J. D. Hood, Y. Yu, J. T. Zhang, N. R. Hutzler, T. Rosenband, and K.-K. Ni. Building one molecule from a reservoir of two atoms. *Science*, 360(6391):900–903, 2018. doi:10.1126/science.aar7797.

[21] J. Wolf, M. Deiß, A. Krükow, E. Tiemann, B. P. Ruzic, Y. Wang, J. P. D'Incao, P. S. Julienne, and J. H. Denschlag. State-to-state chemistry for three-body recombination in an ultracold rubidium gas. *Science*, 358:921, 2018. doi:10.1126/science.aan8721.

[22] A. Goban, R. B. Hutson, G. E. Marti, S. L. Campbell, M. A. Perlin, P. S. Julienne, J. P. D'Incao, A. M. Rey, and J. Ye. Emergence of multi-body interactions in few-atom sites of a fermionic lattice clock. *Nature*, 563:369, 2018. doi:10.1038/s41586-018-0661-6.

[23] Scott E. Pollack, Daniel Dries, and Randall G. Hulet. Universality in three- and four-body bound states of ultracold atoms. *Science*, 326:1683–1686, 2009. doi:10.1126/science.1182840.

[24] S. E. Pollack, D. Dries, R. G. Hulet, K. M. F. Magalhaes, E. A. L. Henn, E. R. F. Ramos, M. A. Caracanhas, and V. S. Bagnato. Collective excitation of a Bose-Einstein condensate by modulation of the atomic scattering length. *Phys. Rev. A*, 81, 2010. doi:10.1103/PhysRevA.81.053627.

[25] Bo Huang, Leonid A. Sidorenkov, Rudolf Grimm, and Jeremy M. Hutson. Observation of the second triatomic resonance in efimov's scenario. *Phys. Rev. Lett.*, 112:190401, 2014. doi:10.1103/PhysRevLett.112.190401.

[26] F. Ferlaino, A. Zenesini, M. Berninger, B. Huang, H.-C. Nägerl, and R. Grimm. Efimov resonances in ultracold quantum gases. *Few-body Systems*, 51:113–133, 2011. doi:10.1007/s00601-011-0260-7.

[27] J. P. D'Incao, J. von Stecher, and Chris H. Greene. Universal four-boson states in ultracold molecular gases: Resonant effects in dimer-dimer collisions. *Phys. Rev. Lett.*, 103:033004, Jul 2009. doi:10.1103/PhysRevLett.103.033004.

[28] Jürgen Berges, Alexander Rothkopf, and Jonas Schmidt. Nonthermal fixed points: Effective weak coupling for strongly correlated systems far from equilibrium. *Phys. Rev. Lett.*, 101:041603, 2008. doi:10.1103/PhysRevLett.101.041603.

[29] Asier Piñeiro Orioli, Kirill Boguslavski, and Jürgen Berges. Universal self-similar dynamics of relativistic and nonrelativistic field theories near nonthermal fixed points. *Phys. Rev. D*, 92:025041, 2015. doi:10.1103/PhysRevD.92.025041.

[30] Raphael Micha and Igor I. Tkachev. Relativistic turbulence: A long way from preheating to equilibrium. *Phys. Rev. Lett.*, 90:121301, 2003. doi:10.1103/PhysRevLett.90.121301.

[31] Guy D. Moore. Condensates in relativistic scalar theories. *Phys. Rev. D*, 93:065043, 2016. doi:10.1103/PhysRevD.93.065043.

[32] J. Berges, K. Boguslavski, S. Schlichting, and R. Venugopalan. Universality far from equilibrium: From superfluid bose gases to heavy-ion collisions. *Phys. Rev. Lett.*, 114: 061601, 2015. doi:10.1103/PhysRevLett.114.061601.

[33] R. Baier, A.H. Mueller, D. Schiff, and D.T. Son. bottom-up thermalization in heavy ion collisions. *Physics Letters B*, 502(1):51 – 58, 2001. doi:https://doi.org/10.1016/S0370-2693(01)00191-5.

[34] J. Berges, K. Boguslavski, S. Schlichting, and R. Venugopalan. Turbulent thermalization process in heavy-ion collisions at ultrarelativistic energies. *Phys. Rev. D*, 89: 074011, 2014. doi:10.1103/PhysRevD.89.074011.

[35] J. M. Deutsch. Quantum statistical mechanics in a closed system. *Phys. Rev. A*, 43: 2046–2049, Feb 1991. doi:10.1103/PhysRevA.43.2046.

[36] Mark Srednicki. Chaos and quantum thermalization. *Phys. Rev. E*, 50:888–901, Aug 1994. doi:10.1103/PhysRevE.50.888.

[37] Mark Srednicki. The approach to thermal equilibrium in quantized chaotic systems. *Journal of Physics A: Mathematical and General*, 32:1163, 1999. doi:10.1088/0305-4470/32/7/007.

[38] Wojciech H. Zurek, Uwe Dorner, and Peter Zoller. Dynamics of a quantum phase transition. *Phys. Rev. Lett.*, 95:105701, Sep 2005. doi:10.1103/PhysRevLett.95.105701.

[39] Marcos Rigol, Vanja Dunjko, and Maxim Olshanii. Thermalization and its mechanism for generic isolated quantum systems. *Nature*, 452:854–858, 2008. doi:10.1038/nature06838.

[40] Jacek Dziarmaga. Dynamics of a quantum phase transition and relaxation to a steady state. *Advances in Physics*, 59(6):1063–1189, 2010. doi:10.1080/00018732.2010.514702.

[41] Anatoli Polkovnikov, Krishnendu Sengupta, Alessandro Silva, and Mukund Vengalattore. Nonequilibrium dynamics of closed interacting quantum systems. *Rev. Mod. Phys.*, 83:863–883, Aug 2011. doi:10.1103/RevModPhys.83.863.

[42] M. Gring, M. Kuhnert, T. Langen, T. Kitagawa, B. Rauer, M. Schreitl, I. Mazets, D. Adu Smith, E. Demler, and J. Schmiedmayer. Relaxation and prethermalization in an isolated quantum system. *Science*, 337(6100):1318–1322, 2012. doi:10.1126/science.1224953.

[43] Marcos Rigol and Mark Srednicki. Alternatives to eigenstate thermalization. *Phys. Rev. Lett.*, 108:110601, Mar 2012. doi:10.1103/PhysRevLett.108.110601.

[44] Miguel A. Cazalilla, Anibal Iucci, and Ming-Chiang Chung. Thermalization and quantum correlations in exactly solvable models. *Phys. Rev. E*, 85:011133, Jan 2012. doi:10.1103/PhysRevE.85.011133.

[45] Christian Gogolin and Jens Eisert. Equilibration, thermalisation, and the emergence of statistical mechanics in closed quantum systems. *Reports on Progress in Physics*, 79(5):056001, 2016. doi:10.1088/0034-4885/79/5/056001.

[46] Luca D'Alessio, Yariv Kafri, Anatoli Polkovnikov, and Marcos Rigol. From quantum chaos and eigenstate thermalization to statistical mechanics and thermodynamics. *Advances in Physics*, 65(3):239–362, 2016. doi:10.1080/00018732.2016.1198134.

[47] Richard J. Fletcher, Alexander L. Gaunt, Nir Navon, Robert P. Smith, and Zoran Hadzibabic. Stability of a unitary bose gas. *Phys. Rev. Lett.*, 111:125303, 2013. doi:10.1103/PhysRevLett.111.125303.

[48] B. S. Rem, A. T. Grier, I. Ferrier-Barbut, U. Eismann, T. Langen, N. Navon, L. Khaykovich, F. Werner, D. S. Petrov, F. Chevy, and C. Salomon. Lifetime of the bose gas with resonant interactions. *Phys. Rev. Lett.*, 110:163202, 2013. doi:10.1103/PhysRevLett.110.163202.

[49] P. Makotyn, C. E. Klauss, D. L. Goldberger, E. A. Cornell, and D. S. Jin. Universal dynamics of a degenerate unitary bose gas. *Nature Physics*, 10(2):116–119, 2014. doi:10.1038/nphys2850.

[50] Ulrich Eismann, Lev Khaykovich, Sébastien Laurent, Igor Ferrier-Barbut, Benno S. Rem, Andrew T. Grier, Marion Delehaye, Frédéric Chevy, Christophe Salomon, Li-Chung Ha, and Cheng Chin. Universal loss dynamics in a unitary bose gas. *Phys. Rev. X*, 6:021025, May 2016. doi:10.1103/PhysRevX.6.021025.

[51] Adam M. Kaufman, M. Eric Tai, Alexander Lukin, Matthew Rispoli, Robert Schittko, Philipp M. Preiss, and Markus Greiner. Quantum thermalization through entanglement in an isolated many-body system. *Science*, 353(6301):794–800, 2016. doi:10.1126/science.aaf6725.

[52] Richard J. Fletcher, Raphael Lopes, Jay Man, Nir Navon, Robert P. Smith, Martin W. Zwierlein, and Zoran Hadzibabic. Two- and three-body contacts in the unitary bose gas. *Science*, 355(6323):377–380, 2017. doi:10.1126/science.aai8195.

[53] Sébastien Laurent, Matthieu Pierce, Marion Delehaye, Tarik Yefsah, Frédéric Chevy, and Christophe Salomon. Connecting few-body inelastic decay to quantum correlations in a many-body system: A weakly coupled impurity in a resonant fermi gas. *Phys. Rev. Lett.*, 118:103403, Mar 2017. doi:10.1103/PhysRevLett.118.103403.

[54] Catherine E. Klauss, Xin Xie, Carlos Lopez-Abadia, José P. D'Incao, Zoran Hadzibabic, Deborah S. Jin, and Eric A. Cornell. Observation of efimov molecules created from a resonantly interacting bose gas. *Phys. Rev. Lett.*, 119:143401, Oct 2017. doi:10.1103/PhysRevLett.119.143401.

[55] Christoph Eigen, Jake A. P. Glidden, Raphael Lopes, Nir Navon, Zoran Hadzibabic, and Robert P. Smith. Universal scaling laws in the dynamics of a homogeneous unitary bose gas. *Phys. Rev. Lett.*, 119:250404, Dec 2017. doi:10.1103/PhysRevLett.119.250404.

[56] Richard J. Fletcher, Jay Man, Raphael Lopes, Panagiotis Christodoulou, Julian Schmitt, Maximilian Sohmen, Nir Navon, Robert P. Smith, and Zoran Hadzibabic. Elliptic flow in a strongly interacting normal bose gas. *Phys. Rev. A*, 98:011601, Jul 2018. doi:10.1103/PhysRevA.98.011601.

[57] Christoph Eigen, Jake A. P. Glidden, Raphael Lopes, Eric A. Cornell, Robert P. Smith, and Zoran Hadzibabic. Universal prethermal dynamics of bose gases quenched to unitarity. *Nature*, 563(7730):221–224, 2018. doi:10.1038/s41586-018-0674-1.

[58] Jake A. P. Glidden, Christoph Eigen, Lena H. Dogra, Timon A. Hilker, Robert P. Smith, and Zoran Hadzibabic. Bidirectional dynamic scaling in an isolated bose gas far from equilibrium. *Nature Physics*, 17(4):457–461, 2021. doi:10.1038/s41567-020-01114-x.

[59] Tin-Lun Ho. Universal thermodynamics of degenerate quantum gases in the unitarity limit. *Phys. Rev. Lett.*, 92:090402, Mar 2004. doi:10.1103/PhysRevLett.92.090402.

[60] J. M. Diederix, T. C. F. van Heijst, and H. T. C. Stoof. Ground state of a resonantly interacting bose gas. *Phys. Rev. A*, 84:033618, Sep 2011. doi:10.1103/PhysRevA.84.033618.

[61] Weiran Li and Tin-Lun Ho. Bose gases near unitarity. *Phys. Rev. Lett.*, 108:195301, May 2012. doi:10.1103/PhysRevLett.108.195301.

[62] Shao-Jian Jiang, Wu-Ming Liu, Gordon W. Semenoff, and Fei Zhou. Universal bose gases near resonance: A rigorous solution. *Phys. Rev. A*, 89:033614, Mar 2014. doi:10.1103/PhysRevA.89.033614.

[63] Sébastien Laurent, Xavier Leyronas, and Frédéric Chevy. Momentum distribution of a dilute unitary bose gas with three-body losses. *Phys. Rev. Lett.*, 113:220601, Nov 2014. doi:10.1103/PhysRevLett.113.220601.

[64] Xiao Yin and Leo Radzihovsky. Quench dynamics of a strongly interacting resonant bose gas. *Phys. Rev. A*, 88:063611, Dec 2013. doi:10.1103/PhysRevA.88.063611.

[65] A. G. Sykes, J. P. Corson, J. P. D'Incao, A. P. Koller, C. H. Greene, A. M. Rey, K. R. A. Hazzard, and J. L. Bohn. Quenching to unitarity: Quantum dynamics in a three-dimensional bose gas. *Phys. Rev. A*, 89:021601, Feb 2014. doi:10.1103/PhysRevA.89.021601.

[66] Maurizio Rossi, Luca Salasnich, Francesco Ancilotto, and Flavio Toigo. Monte carlo simulations of the unitary bose gas. *Phys. Rev. A*, 89:041602, Apr 2014. doi:10.1103/PhysRevA.89.041602.

[67] D. Hudson Smith, Eric Braaten, Daekyoung Kang, and Lucas Platter. Two-body and three-body contacts for identical bosons near unitarity. *Phys. Rev. Lett.*, 112:110402, Mar 2014. doi:10.1103/PhysRevLett.112.110402.

[68] Eric Braaten, Daekyoung Kang, and Lucas Platter. Universal relations for identical bosons from three-body physics. *Phys. Rev. Lett.*, 106:153005, Apr 2011. doi:10.1103/PhysRevLett.106.153005.

[69] Félix Werner and Yvan Castin. General relations for quantum gases in two and three dimensions. ii. bosons and mixtures. *Phys. Rev. A*, 86:053633, Nov 2012. doi:10.1103/PhysRevA.86.053633.

[70] M. Kira. Coherent quantum depletion of an interacting atom condensate. *Nature Communications*, 6(1):6624, 2015. doi:10.1038/ncomms7624.

[71] Marcus Barth and Johannes Hofmann. Efimov correlations in strongly interacting bose gases. *Phys. Rev. A*, 92:062716, Dec 2015. doi:10.1103/PhysRevA.92.062716.

[72] John P. Corson and John L. Bohn. Bound-state signatures in quenched bose-einstein condensates. *Phys. Rev. A*, 91:013616, Jan 2015. doi:10.1103/PhysRevA.91.013616.

[73] Tommaso Comparin and Werner Krauth. Momentum distribution in the unitary bose gas from first principles. *Phys. Rev. Lett.*, 117:225301, Nov 2016. doi:10.1103/PhysRevLett.117.225301.

[74] Xiao Yin and Leo Radzihovsky. Postquench dynamics and prethermalization in a resonant bose gas. *Phys. Rev. A*, 93:033653, Mar 2016. doi:10.1103/PhysRevA.93.033653.

[75] Shao-Jian Jiang, Jeff Maki, and Fei Zhou. Long-lived universal resonant bose gases. *Phys. Rev. A*, 93:043605, Apr 2016. doi:10.1103/PhysRevA.93.043605.

[76] Yijue Ding and Chris H. Greene. Renormalized contact interaction in degenerate unitary bose gases. *Phys. Rev. A*, 95:053602, May 2017. doi:10.1103/PhysRevA.95.053602.

[77] M. W. C. Sze, A. G. Sykes, D. Blume, and J. L. Bohn. Hyperspherical lowest-order constrained-variational approximation to resonant bose-einstein condensates. *Phys. Rev. A*, 97:033608, Mar 2018. doi:10.1103/PhysRevA.97.033608.

[78] D. Blume, M. W. C. Sze, and J. L. Bohn. Harmonically trapped four-boson system. *Phys. Rev. A*, 97:033621, Mar 2018. doi:10.1103/PhysRevA.97.033621.

[79] V. E. Colussi, J. P. Corson, and J. P. D'Incao. Dynamics of three-body correlations in quenched unitary bose gases. *Phys. Rev. Lett.*, 120:100401, Mar 2018. doi:10.1103/PhysRevLett.120.100401.

[80] José P. D'Incao, Jia Wang, and V. E. Colussi. Efimov physics in quenched unitary bose gases. *Phys. Rev. Lett.*, 121:023401, Jul 2018. doi:10.1103/PhysRevLett.121.023401.

[81] V. E. Colussi, B. E. van Zwol, J. P. D'Incao, and S. J. J. M. F. Kokkelmans. Bunching, clustering, and the buildup of few-body correlations in a quenched unitary bose gas. *Phys. Rev. A*, 99:043604, Apr 2019. doi:10.1103/PhysRevA.99.043604.

[82] S. Musolino, V. E. Colussi, and S. J. J. M. F. Kokkelmans. Pair formation in quenched unitary bose gases. *Phys. Rev. A*, 100:013612, Jul 2019. doi:10.1103/PhysRevA.100.013612.

[83] V. E. Colussi, H. Kurkjian, M. Van Regemortel, S. Musolino, J. van de Kraats, M. Wouters, and S. J. J. M. F. Kokkelmans. Cumulant theory of the unitary bose gas: Prethermal and efimovian dynamics. *Phys. Rev. A*, 102:063314, Dec 2020. doi:10.1103/PhysRevA.102.063314.

[84] M. W. C. Sze and J. L. Bohn. Two-step production of resonant bose-einstein condensates. *Phys. Rev. A*, 99:033606, Mar 2019. doi:10.1103/PhysRevA.99.033606.

[85] E. J. Halperin, M. W. C. Sze, J. P. Corson, and J. L. Bohn. Stable production of a strongly interacting bose-einstein condensate via mode matching. *Phys. Rev. A*, 100: 013608, Jul 2019. doi:10.1103/PhysRevA.100.013608.

[86] Stefano Giorgini, Lev P. Pitaevskii, and Sandro Stringari. Theory of ultracold atomic fermi gases. *Rev. Mod. Phys.*, 80:1215–1274, Oct 2008. doi:10.1103/RevModPhys.80.1215.

[87] M. Holland, S. J. J. M. F. Kokkelmans, M. L. Chiofalo, and R. Walser. Resonance superfluidity in a quantum degenerate fermi gas. *Phys. Rev. Lett.*, 87:120406, Aug 2001. doi:10.1103/PhysRevLett.87.120406.

[88] S. J. J. M. F. Kokkelmans, J. N. Milstein, M. L. Chiofalo, R. Walser, and M. J. Holland. Resonance superfluidity: Renormalization of resonance scattering theory. *Phys. Rev. A*, 65:053617, May 2002. doi:10.1103/PhysRevA.65.053617.

[89] F Chevy and C Salomon. Strongly correlated bose gases. *J. Phys. B*, 49(19):192001, sep 2016. doi:10.1088/0953-4075/49/19/192001.

[90] J. P. D'Incao, H. Suno, and B. D. Esry. Limits on universality in ultracold three-boson recombination. *Phys. Rev. Lett.*, 93:123201, Sep 2004. doi:10.1103/PhysRevLett.93.123201.

[91] Leo Radzihovsky, Jae Park, and Peter B. Weichman. Superfluid transitions in bosonic atom-molecule mixtures near a feshbach resonance. *Phys. Rev. Lett.*, 92:160402, Apr 2004. doi:10.1103/PhysRevLett.92.160402.

[92] Leo Radzihovsky, Peter B. Weichman, and Jae I. Park. Superfluidity and phase transitions in a resonant bose gas. *Annals of Physics*, 323(10):2376–2451, 2008. ISSN 0003-4916. doi:https://doi.org/10.1016/j.aop.2008.05.008.

[93] M. W. J. Romans, R. A. Duine, Subir Sachdev, and H. T. C. Stoof. Quantum phase transition in an atomic bose gas with a feshbach resonance. *Phys. Rev. Lett.*, 93: 020405, Jul 2004. doi:10.1103/PhysRevLett.93.020405.

[94] Yu-Wen Lee and Yu-Li Lee. Quantum phase transition in an atomic bose gas near a feshbach resonance. *Phys. Rev. B*, 70:224506, Dec 2004. doi:10.1103/PhysRevB.70.224506.

[95] Arkadiusz Wójs, Csaba Tőke, and Jainendra K. Jain. Global phase diagram of the fractional quantum hall effect arising from repulsive three-body interactions. *Phys. Rev. Lett.*, 105:196801, Nov 2010. doi:10.1103/PhysRevLett.105.196801.

[96] Paulo F. Bedaque and Jos P. DIncao. Superfluid phases of the three-species fermion gas. *Annals of Physics*, 324(8):1763 – 1768, 2009. ISSN 0003-4916. doi:https://doi.org/10.1016/j.aop.2009.02.005.

[97] Yusuke Nishida. New type of crossover physics in three-component fermi gases. *Phys. Rev. Lett.*, 109:240401, Dec 2012. doi:10.1103/PhysRevLett.109.240401.

[98] Yusuke Nishida. Phases of a bilayer fermi gas. *Phys. Rev. A*, 82:011605, Jul 2010. doi:10.1103/PhysRevA.82.011605.

[99] D. S. Petrov. Three-body interacting bosons in free space. *Phys. Rev. Lett.*, 112: 103201, Mar 2014. doi:10.1103/PhysRevLett.112.103201.

[100] Shimpei Endo, Antonio M. García-García, and Pascal Naidon. Universal clusters as building blocks of stable quantum matter. *Phys. Rev. A*, 93:053611, May 2016. doi:10.1103/PhysRevA.93.053611.

[101] Pascal Naidon, Shimpei Endo, and Antonio M García-García. Scattering of universal fermionic clusters in the resonating group method. *J. Phys. B*, 49(3):034002, 2016. doi:10.1088/0953-4075/49/3/034002.

[102] Swann Piatecki and Werner Krauth. Efimov-driven phase transitions of the unitary bose gas. *Nature Communications*, 5(1):3503, 2014. doi:10.1038/ncomms4503.

[103] Yangqian Yan and D. Blume. Temperature dependence of small harmonically trapped atom systems with bose, fermi, and boltzmann statistics. *Phys. Rev. A*, 90:013620, Jul 2014. doi:10.1103/PhysRevA.90.013620.

[104] Aurel Bulgac. Dilute quantum droplets. *Phys. Rev. Lett.*, 89:050402, Jul 2002. doi:10.1103/PhysRevLett.89.050402.

[105] Wilhelm Zwerger. Quantum-unbinding near a zero temperature liquid–gas transition. *J. Stat. Mech.*, 2019(10):103104, 2019. doi:10.1088/1742-5468/ab3ccc.

[106] P. M. A. Mestrom, V. E. Colussi, T. Secker, G. P. Groeneveld, and S. J. J. M. F. Kokkelmans. van der waals universality near a quantum tricritical point. *Phys. Rev. Lett.*, 124:143401, Apr 2020. doi:10.1103/PhysRevLett.124.143401.

[107] Elizabeth A. Donley, Neil R. Claussen, Simon L. Cornish, Jacob L. Roberts, Eric A. Cornell, and Carl E. Wieman. Dynamics of collapsing and exploding bose–einstein condensates. *Nature*, 412(6844):295–299, 2001. doi:10.1038/35085500.